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ON THE DANGER OF REDUNDANCIES IN SOME AEROSPACE MECHANISMS*

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ABSTRACT

This paper attempts to show that redundancies in some aerospace mechanisms do not generally improve the odds for success. Some of these redundancies may even be the very cause for failure of the system. To illustrate this fallacy, two designs based on the Control of Flexible Structures I (COFS I) Mast deployer and retractor assembly (DRA) are presented together with novel designs to circumvent such design inadequacies, while improving system reliability.

INTRODUCTION

One of the general principles held closely and dearly by mechanical designers and engineers is the incorporation of redundancies in the design of their mechanical and electromechanical systems. For good system reliability, redundancies are incorporated to improve the chances for success, and generally do; however, there are some types of redundancies that fail to do so. In fact, this paper, in describing two aerospace mechanism designs, will illustrate that some redundancies may decrease the chances for system success. Although the set of such undesirable types of redundancies described herein is small, it is worth documenting such types that do not perform to expectation. Other approaches can be taken instead to improve the odds. Redundancies can also introduce other penalties (such as space, weight, efficiency and fabrication costs) which should be weighed against the expected benefits of the redundancies introduced into the system.

One type of redundancy that is undesirable relates to conditions within the system. A given failure of a component or subsystem may change the environment such that the redundant component or subsystem does not perform to its expected level. Such a redundancy degradation can, at times, be anticipated so that designs around

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the obstacle can be adopted. As an example, failures occurred in some recent development and deployment tests conducted on the Magellan (Venus Mapper) Spacecraft when a particular lot of pyrotechnic pin pullers, ones that incorporate a redundant initiator, failed to function properly. As part of an engineering evaluation, the contractor conducting the tests determined that

1. The shock pulse from the first initiator could prove sufficient to permanently distort the bore of the pin puller, thereby preventing piston motion. A subsequent firing of the second initiator would not improve this situation. Fabrication and quality assurance problems were also present in these units.

2. Further design consideration by others revealed that if the first initiator's output was insufficient, firing this initiator could contaminate the interior surface with sufficient particulate deposits to inhibit free piston movement if such movement had not already taken place. It is possible that enough particulate contamination could be introduced between the piston and bore to prevent any piston motion with a subsequent firing of the second initiator.

This paper considers another type of undesirable redundancy which introduces a condition of over constraint to aerospace mechanisms. To adequately explain and illustrate this type of redundancy, two mechanism designs within the COFS I DRA will be used to show how such a type of redundancy can actually be the cause for system failure. The two mechanisms are the lead-screw drive and the diagonal fold-arm bell-crank linkage. In the sections that follow, a description is given of the design of each of these mechanisms, how they function within the COFS I DRA, how their expected redundancy can cause failure, and how the design can be improved.

BACKGROUND

As a subset of COFS I, the Mast Flight System (MFS), figure 1, incorporating a reusable, deployable-restowable truss beam as a test bed, was conceived to bridge the gap between ground and on-orbit modal verification, and validation of control methodologies. A description of the specific subsystems of the MFS, of which the deployer and retractor assembly (DRA) is one of the major functional components, can be found in reference 1.

OPERATION OF THE COFS DEPLOYER/RETRACTOR ASSEMBLY (DRA)

The main function of the DRA is to deploy and retract the beam out of and into the Shuttle payload bay in a continuous, smooth motion. This sequence of deployment and retraction is shown in figure 2. Figure 3 shows the DRA with

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the beam partially deployed. Central to the DRA is an annular box called the upper drive assembly. This box contains two sets of mechanisms. One is a gear train designed for simultaneous power transmission to three lead-screws used to deploy or retract the beam. The other is a spatial linkage designed to unlock and open the beam's diagonal latches and hence initiate folding of the beam during the retraction process. These mechanisms are illustrated in figure 4.

The deploy or restow drive mechanism is powered by a deployer motor via a gearbox so as to enable the lead-screws to change their direction and speed of rotation. The mechanism consists of six drive shafts, laid end-to-end to form a loop, much like the sides of a hexagon. At the ends of each shaft are bevel gears, so that power may be transmitted from one shaft to the next, around this hexagonal loop, back to itself. Power take-offs for the lead-screws occur at every other set of beveled gears. The redundancy arises from the continuous loop--failure of any drive shaft or bevel gear will not disrupt the ability of this mechanism to transmit power to the set of three lead-screws. Such a gearing system is called a recirculating gear train [references 2-4]. Other types of power recirculating arrangements have been used in the testing of belts and chain drives [references 5 and 6].

In the process of deploying the beam, the deployer drive motor rotates in a direction such that the lead-screws move the nodal fittings (corner bodies) located at the corners of the beam. As the corner bodies ride along the lead-screws, the immediate folded stack bay of the beam begins to unfold. Since the lead-screw rotation is continuous, the unfolding, and hence the deployment of the beam, is smooth and continuous. The reverse is also true for the retraction of the beam. At the deployed position for each beam bay-pair, the diagonal links are straightened and the mid-span hinges and latches are spring loaded so that the beam behaves as a structure.

To begin retracting the beam, the same spring loaded latches on the diagonal links must be unlocked to permit the diagonal links to fold. To fold these spring latches, the diagonal fold-arm drive system is used. Simultaneously, as these latches are being folded, the separate deployer motor is driving the lead-screws in the restow direction. This causes the corner bodies to move down into the DRA, thereby completing the folding and stowing of each bay-pair of the beam. This sequence is repeated until the beam is restowed.

In the following sections, an examination of how redundancies in the lead-screw drive gear train and in the bell-crank linkage could be the very factors that can cause failures within the DRA will be presented. This examination begins with the bell-crank mechanism.

BELL-CRANK LINKAGE

In the bell-crank linkage (figure 4) that is located in the upper drive assembly (figure 3) of the DRA, a crank-and-rocker linkage, driven by the retractor motor through a diagonal fold-arm drive gear, is concatenated to the bell-crank. Rotation of the diagonal fold-arm drive motor results in oscillatory motion of the bell-crank linkage. This linkage consists of six triangular oscillatory members, or links, that are located at the corners of a hexagon. These triangular links are connected to each other by six straight members to form a hexagonal continuous or closed-loop. While minimizing backlash, this loop is anticipated to provide redundancy in the event of failure of any of the bell-crank or straight link members. A power take-off at each alternate bell-crank, transfers the oscillatory motion of the bell-crank linkage drive to a spatial six-bar linkage that transmits power to the upper and lower diagonal fold-arms. These diagonal fold-arms press on the near-over-center hinge latches to effect folding of the diagonal during the initial stages of the retraction process for each bay-pair of the beam.

Next, consider the six couplers that link the bell-cranks together to form the hexagonal loop. Normally, only five such links are needed. In the event any one of these links were to fail, a sixth coupler link was incorporated to complete the loop, thereby ensuring that the bell-crank linkage would still perform its function. In this way, a redundant power path to retract the beam back into the canister is still maintained to all the diagonal fold-arms should any coupler link fail. Such a redundancy has obvious advantages. It absolves the need for a totally separate system that would increase cost, weight, complexity and space requirements; and, according to the subcontract designers, it would also provide some degree of structural integrity to the mechanism in the form of lower system backlash.

General Observations on Mobility

Careful design considerations are needed to introduce this sixth coupler link. In fact, without judicious dimensional choices for the bell-crank mechanism, the resulting hexagonal loop (with the sixth coupler link) will act as a structure, not a mechanism and therefore will not move! A brief proof follows:

> A kinematic equivalent for an arbitrarily dimensioned bell-crank mechanism is shown in figure 5. In this figure, link #1 is the ground (fixed) link. Applying the degree-of-freedom (d.o.f.) equation attributed to Gruebler [reference 7 and 8] for this linkage we have;
>
> Link #1 is the ground link.
>
> Using the d.o.f. equation, $F = \lambda(L-j-1) + \Sigma f_i$
>
> Where for planar mechanism,
> λ = Mobility number = 3
> L = Total # of links = 13,
> j = Total # of joints = 18, and
> f_i = d.o.f. of the i^{th} joint = 1.
>
> substituting $F = 3(13-18-1) + 18$
>
> so that $F = 0$

Which states that the bell-crank mechanism is a zero d.o.f. system and is therefore a structure and will not move!

Special Dimensions for the Bell-Crank Mechanism

There are special dimensional requirements for this linkage that will permit the bell-crank mechanism to exhibit a single d.o.f. The theory is based on that of a folding linkage [reference 8]. The folding linkage is a four-bar where the dimensions of its opposite links are equal, such that the four-bar constitutes a parallelogram. A principal characteristic of the folding linkage is that any given angular rotation on the input link is exactly duplicated at the output link. Such a linkage therefore (a) ensures a design with one d.o.f., (b) allows the bell-crank and folding arm members to operate as a mechanism, and (c) maintains the synchronization of all the folding arms (upper and lower pairs)--a total of six in the DRA. Based on the characteristics of the folding linkage and on sufficiency conditions, a workable design for the bell-crank mechanism would be

1. All coupler links must be the same length (from figure 5, they are links #3, 5, 7, 9, 11, 13), and that same length must also be equal to the distance between two adjacent ground pivots of the bell-cranks.

2. All rocker links or sides of the bell-cranks (such as links #2a, 2b, 4a, 4b, 6a, 6b, 8a, 8b, 10a, 10b, 12a and 12b) are of the same length.

3. The angles (α) subtended by the bell-cranks at the pivots must all be equal to 60°.

With the above special dimensions, the bell-crank mechanism will exhibit a single d.o.f. and will therefore move. Under this set of circumstances, the d.o.f. equation will no longer apply. While the above design simplifies the choice of dimensions, the number of parts are still a point of concern. The high part count contributes to problems in tolerance buildup, reliability, cost, weight and space. A more optimal approach to the design with improvements in all these factors will be discussed later.

Danger of Over Constraint Redundancies

The loop arrangement for the bell-crank mechanism ensures a dual path for power transmission to the upper and lower diagonal fold-arms in the event that a coupler link within the mechanism fails. However, this redundancy may only be academic. Recall that the bell-crank mechanism under general dimensions forms a structure and is therefore immobile. The introduction of the sixth coupler link as a redundancy has caused the mechanism to become over constrained. Fortunately, with special dimensional requirements, the bell-crank mechanism can be made movable with a single d.o.f. However, these special dimensional requirements must be observed at all times during the planned operation of the DRA. The problem is, in the hostile space environment, temperature gradients across the mechanism could cause these dimensional requirements to be violated. This could result in locking up the bell-crank mechanism (reverting it back to a structure) or could cause high link- and bearing-loadings within the mechanism. Even in the absence of temperature gradients, the costs and complexity of ensuring tight tolerancing may well be undesirable.

This bell-crank mechanism therefore serves to illustrate the danger of introducing a redundancy into a mechanism that will result in an over constrained system. With special dimensional requirements, the mechanism may be made movable. However, the strict requirements of dimensional control in hostile environments may not be readily realized in practice. This could bring about failure of the system, ironically due to that very redundancy.

While this example is based on that for a linkage mechanism, the principle is equally applicable to gear drive mechanisms. The next section discusses the danger of such over constraint redundancies in the lead-screw drive mechanism of the DRA.

LEAD-SCREW DRIVE MECHANISM

The lead-screw drive mechanism is powered by a deployer motor via a gearbox which enables the lead-screws to change their direction and speed of rotation. In an arrangement similar to the bell-crank mechanism, the lead-screw drive mechanism consists of six drive shafts, laid end-to-end to form a loop, much like the sides of a hexagon shown in figure 4. At the ends of each shaft are bevel gears, so that power may be transmitted from one shaft to the next, around this hexagonal loop, back to itself. It can be seen that power take-offs for the lead-screws occur at every other set of beveled gears in the hexagonal loop. The redundancy arises from the continuous loop--failure of any drive shaft or bevel gear will not disrupt the ability of this mechanism to transmit power to the set of three lead-screws. Such a gearing system is called a recirculating gear train which can be found in many machines, although rather infrequently, for a good reason.

A quick investigation into the general mobility of such a gear drive set-up would show a zero d.o.f. A brief proof for this system follows:

Again applying the d.o.f. equation [reference 7 and 8] for this loop we have;

With link #1 as the ground link.

Using the d.o.f. equation, $F = \lambda(L-j-1) + \Sigma f_i$

Where for planar mechanism,

λ = Mobility number = 3
L = Total # of links = 13,
j = Total # of joints = 24, and
Σf_i = Total d.o.f. of all joints = 36.

substituting $F = 3(13-24-1) + 36 = 0$

so that $F = 0$

Which states that, as in the bell-crank mechanism, this gear train has a zero d.o.f. and is therefore a structure!

This gear train is only operable when special dimensions are instituted into the design. The difficulty of maintaining the special dimensions needed in recirculating gear trains testifies to the generally high tooth loadings and low power transmission efficiencies observed. This is precisely what is observed in gear torque testing machinery which also has similar recirculating gear train arrangements [reference 9]. With inadequate design, the resultant low power transmission efficiency could cause failure of the mechanism to perform its mission satisfactorily, if at all. In fact, during tests of a DRA feasibility of concept model, a gear box failed and higher than predicted drive motor loads were experienced. This was believed due, in part, to a lack of recognition of the need to achieve and maintain special dimensions.

RECOMMENDATION ON DESIGN IMPROVEMENTS

The introduction of an additional link or drive shaft has caused the respective mechanisms to become over constrained. Such kinematic structures for power transfer, although commonly found within subcomponents such as constant velocity joints and universal joints [references 10 and 11], may not be suitable for aerospace applications. Therefore other approaches should be pursued.

One approach to eliminate the effects of over constraint within the system is not to introduce it in the first place. For example, it is possible to design the coupler links and the gear shafts to ensure that their failure would not occur. Such would be the simplest approach if that is possible within the available space and weight requirements.

Another approach is to use circular ring gear arrangements as illustrated in figure 6. This design consists of two large ring gears that rotate concentric to the axis of the canister. The innermost ring gear is driven by the deployer motor and power is fed off to three gears to drive each of the three lead-screws. The use of a ring gear makes the process of coordinating the rotation of the lead-screws a trivial matter when compared to the present design.

In a similar manner, the outermost ring gear driven by the diagonal folding mechanism motor, pushes and pulls on three push-pull cables as it oscillates back and forth. These cables, after going through a very gradual 90° turn to orient them parallel to the beam axis, drive the upper diagonal fold-arms which in turn are coordinated with the respective lower diagonal fold-arms via a coupler link. To save weight, this ring gear could be made up of gear sectors.

In comparison to the present design, this ring gear arrangement would save space, reduce part count, and improve reliability.

SUMMARY

Two designs of mechanisms that have redundancies built-in have been shown, paradoxically, to be the very elements that can cause failure of the mechanism to perform its function. In each of these designs, the introduction of the redundancy causes the mechanism to become kinematically over constrained. While the over constraint may be eliminated with special dimensional requirements placed on the mechanism, these requirements may not be achievable in the hostile environment of space.

While redundancies do indeed generally improve the odds for mission success, redundancies also exist that do not follow this general philosophy. The dangers of such fallacies, if unexplored and not emphasized, may lead to significant redesign or loss of valuable experiments.

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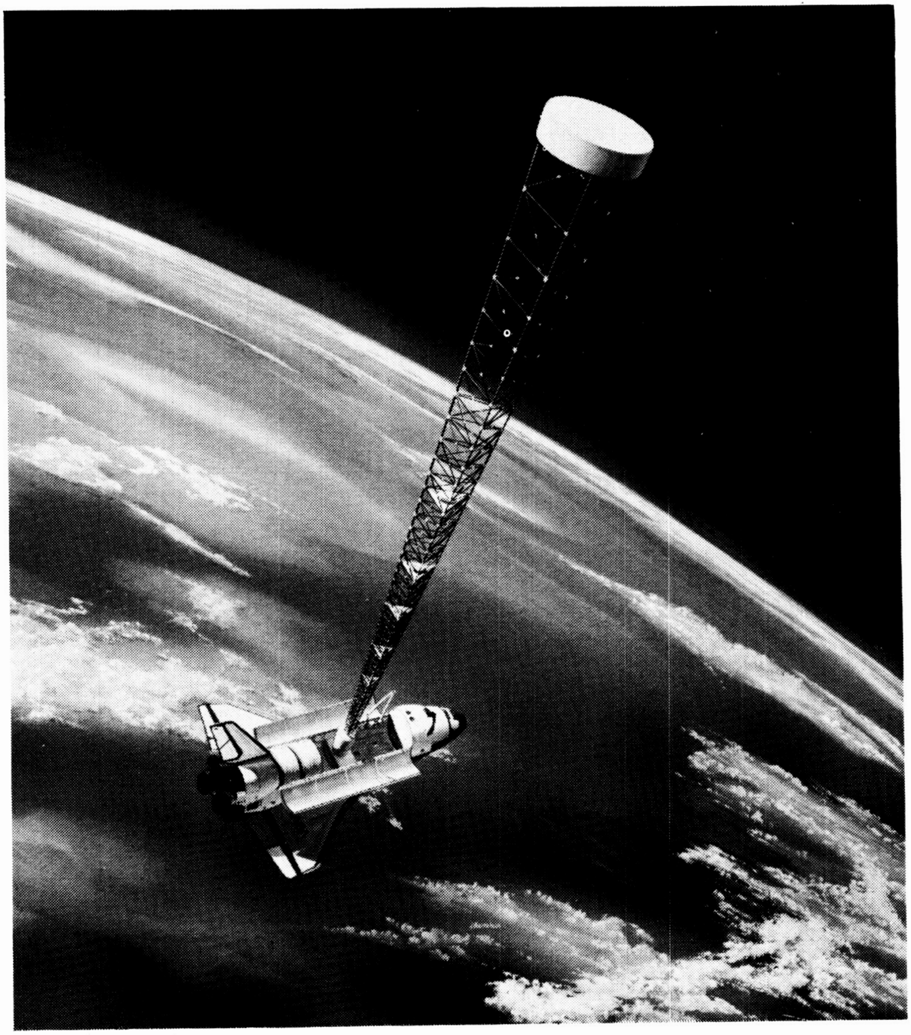

Figure 1.- Deployed 60 Meter Mast Beam

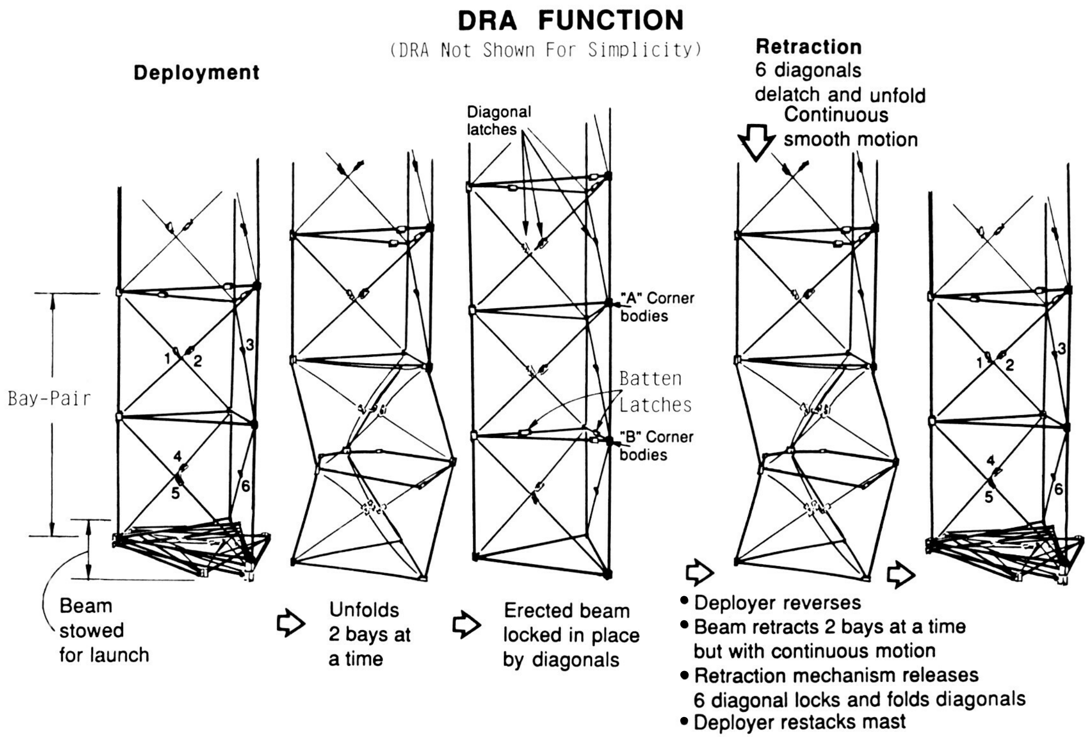

Figure 2.- Mast Beam Deployment/Retraction Sequence

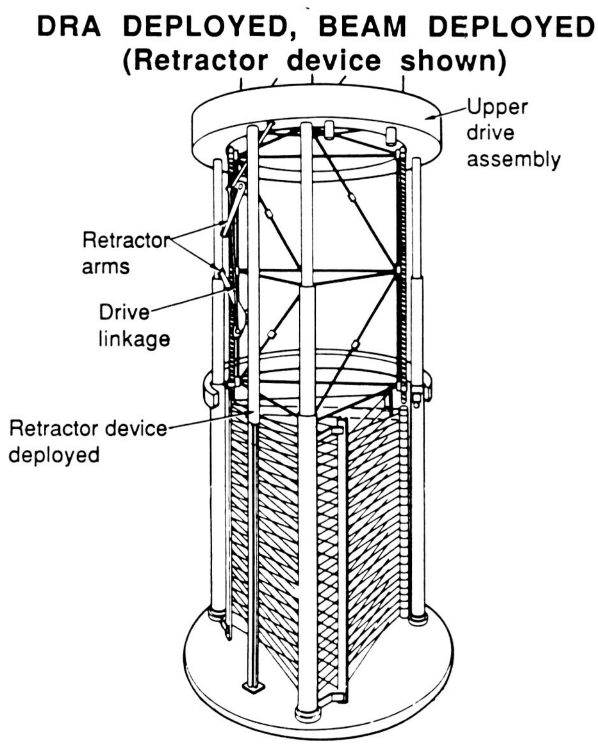

Figure 3.- DRA Deployed, Beam Partially Deployed
(Typical Retractor Device Shown)

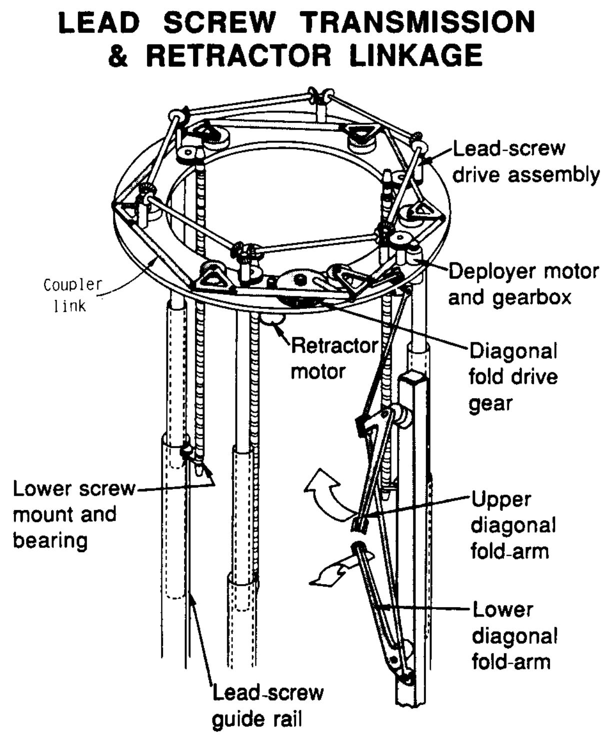

Figure 4.- Lead-Screw and Fold-Arm (Retractor) Mechanism

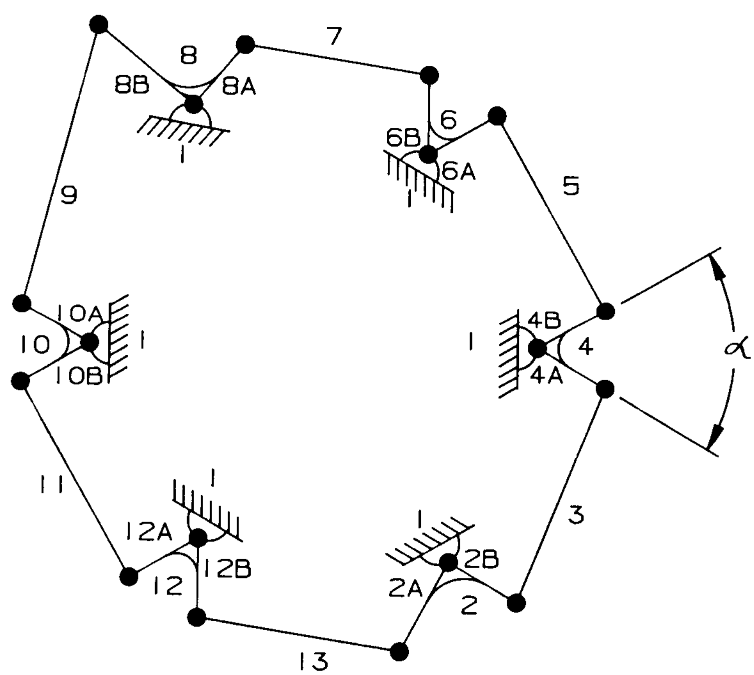

Figure 5.- Bell-Crank Mechanism Kinematic Equivalent

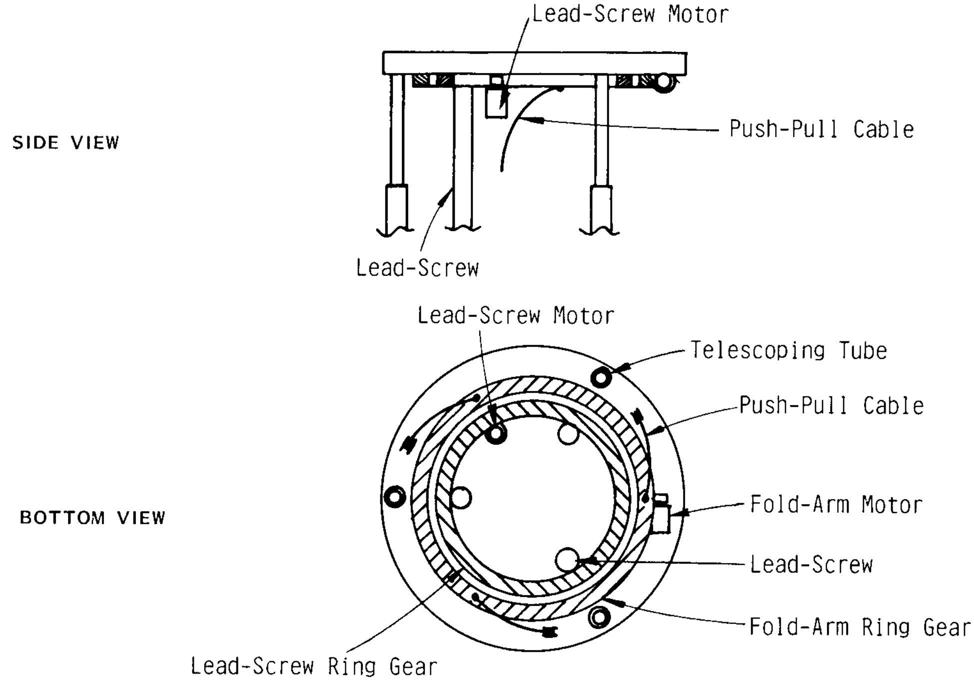

Figure 6.- Circular Gear Arrangement